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An ANSERLIN Array for Mobile Satellite Applications

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ABSTRACT

Design, analysis, construction and test of linear arrays of ANSERLIN (ANnular SEctor, Radiating LINe) elements are reported and discussed. Due to feeding simplicity and easy construction as well as good CP performance, a planar array composed of a number of such linear arrays each producing a shaped beam tilted in elevation, is a good candidate as a vehicle-mounted mechanically steered antenna for Mobile Satellite Applications.

A single level construction technique was developed that makes this type of array very cost competitive with other low-profile arrays. An asymmetric 19.5" long four-element array was fabricated and tested with reasonable performance. A smaller five-element symmetric array (16" long) was also designed and tested capable of operating in either sense of circular polarization. Mutual coupling, however, seems to be a problem. Efforts have been made to successfully reduce this effect.

INTRODUCTION

(a) System Requirements

Ground-based antennas for mobile satellite applications must meet rather severe requirements, not the least of which is low cost. They must also provide adequate gain for circular polarization and, to operate at an arbitrary location in CONUS, the gain must be maintained at all elevation angles between 20 and 60 degrees above the horizon. Furthermore, the beam must track the satellite throughout maneuvers of the vehicle. Azimuth tracking has been previously demonstrated using mechanically steered antennas[1]. However, the antenna used for that system was a tilted broadside array with a relatively high profile. The goal of the study reported here is to provide a low-profile planar array with equivalent or better performance.

(b) ANSERLIN antennas

The annular sector, radiating-line (ANSERLIN) antennas are well suited to this application[2]. They have low-profile, low axial ratio, are well matched over a wide band, and can be designed to provide wide range of aperture tapers in a single series-fed configuration. The geometry of a single ANSERLIN element is shown in Figure 1. An annular sector of strip conductor over a ground plane is fed by a triangular fin transmission line of the same characteristic impedance. The fin transmission line can be excited at its small end by the center conductor of a coax cable, or by a narrow microstrip line. A second port, identical in geometry to the first, is provided at the other end of the annular conductor. In this manner, the entire antenna is constructed to be of uniform characteristic impedance. When one port is terminated in the matching impedance, the input impedance at the other port is invariant with frequency and equal to the characteristic impedance of the lines comprising the complete structure. Return losses of over 20 dB across bands as wide as 8:1 are typical.

Since no reflections occur at any point along the annular sector, a wave produced by excitation of one port travels around the sector with progressive phase that is proportional to the azimuth angle (ϕ) traversed. Traveling-wave sources with a phase shift of one degree per degree azimuth angle ($m' = 1$ in $\exp[-jm'\phi]$) are known to produce a low axial ratio

(AR) over an appreciable portion of the single-lobed radiation pattern. This condition is achieved by the ANSERLIN antenna at a particular frequency. However, a wide pattern bandwidth is achieved when frequency is varied about that frequency. Neither power gain nor axial ratio suffer significantly over bandwidths as great as 30%. The first consequence of changing frequency away from the m' = 1 operating point is a squinting of the beam in the plane orthogonal to the plane of symmetry of the element. For the MSAT application this squint of the element pattern can be used to advantage in achieving the desired low-angle coverage.

ARRAY DESIGN PROCEDURES

(a) Sector Patterns by Fourier Series

A Fourier synthesis procedure is used to calculate the required excitations coefficients of the array for obtaining a sector pattern. Both symmetric and asymmetric coefficients about the center of the array can be obtained using this synthesis procedure.

The asymmetric realizations results in excitation coefficients that are monotonically decreasing along the array, more easily realized with ANSERLIN elements.

(b) Tilted Element Patterns

Using the above synthesis procedure it is possible to find excitation coefficients that would yield a space factor with approximately uniform coverage of the angles from 20 to 60 degrees above the horizon. However, if the element pattern has a maximum at zenith (90 degrees above the horizon), then the space factor must be distorted to emphasize the low angles to compensate for the reduction in directive gain of the element at those angles. This makes the space factor much more difficult to realize with only a few elements. It was thus considered important to make use of the tilted element patterns that are readily achieved by operating ANSERLIN elements at frequencies where m' is either greater or less than unity.

Since the tilt is more pronounced in the case of m' > 1, the initial designs for the MSAT array were carried out for this case. Figure 2 shows typical tilted element patterns for two orthogonal linear polarizations. These patterns were computed using patch basis functions to represent the current on the ANSERLIN element. The expansion coefficients for the current were found by implementing a moment method code on a Cray supercomputer. The computed results are in good agreement with measured patterns. The maximum tilt, at m' = 1.25, is $\theta_0 \approx 15°$. A pattern that is tilted in the opposite direction (m' = 0.8) is shown in Figure 3. In this case the achievable tilt is less and the difference between θ and ϕ polarizations is somewhat greater, but the AR in the coverage region remains very good. In both cases, the field at θ = -70° (20° above the horizon) is several dB higher than it would be for m' = 1.

(c) Computer-Aided Synthesis

The synthesis procedure produces excitation coefficients that give a radiation pattern that approximates the desired one. However, due to the limited number of elements, this procedure provides only a rather rough approximation of the pattern and there is still room for significant improvement by minor adjustments in the excitation coefficients. Rather than using a time-consuming experimental procedure to make these adjustments, a numerical method was used. The procedure is built around a computer program that minimizes a multivariable non-linear function. The routine performs a minimization of a performance index, PI, which is the single-valued sum of the differences of squares

$$PI = \Sigma (a_n^2 - b_n^2), n = 0,1,...,N$$

where a_n represents one of N values of the calculated magnitude of the array pattern at an elevation angle, θ_n, and b_n represents the magnitude of the desired pattern at the same location. To simplify matters, uniform spacing is assumed during the computer optimization of the array design. The element spacing is fixed and an initial set for the excitation coefficients is determined. The starting point can be obtained by using an approximate synthesis technique, such as referred to in (a).

In the program written to implement this process, the desired pattern can be entered in one of two ways. The simplest is to enter a sector pattern. To do this, the upper and lower limits of $\cos(\theta)$ are entered with the number of sample points. The program then constructs a desired pattern with a magnitude of unity over the desired limits of θ and zero elsewhere. The second method is useful in fine tuning the pattern. it allows the normalized value of the desired pattern to be entered at incremental steps of θ. This is particularly appropriate MSAT array design which requires coverage at lower elevation angles. The beam can be "pushed" toward the horizon to improve coverage at these lower angles. This is done by increasing the weight of the error function at lower elevation angles. This technique was employed to obtain the excitation coefficients used in producing the pattern shown in Figure 4.

(d) Realization of Excitations Through Scattering Parameters

Since each ANSERLIN element is a two-port device, it is convenient to characterize its performance in the feeder network of the array in terms of scattering parameters. Realization of the excitation coefficients is then attempted by means of variations in the ratios of outer to inner radii of the annular sectors[3]. At m' = 1.25, the magnitude of S_{21} can be changed between approximately 0.5 and 5.0 dB by varying the diameter ratio between 1.5 and 7.0. The particular ratio that is required to obtain a given magnitude for S_{21} is determined from data acquired by measuring the scattering parameters of several ANSERLIN elements[3].

Neglecting mutual coupling, the S_{12} parameters across the array elements can be easily related to their excitation coefficients using simple power relations. Once the excitation coefficients are determined by the synthesis procedure, the required scattering parameters are found which are then used in deciding the geometry of the elements.

(e) Progressive and Quasi-Progressive Phasing

One drawback in using a tilted beam with m' > 1 is the size of the ANSERLIN elements. The overall size of the array can be reduced significantly by using an element with m' < 1. Another factor not considered in the above procedures, is the possibility of reducing production costs by being able to use the same array for either sense of circular polarization. A series-fed array of ANSERLIN elements is capable of giving identical shape of radiation patterns for both right-hand and left-hand senses if the array is made so that it is symmetrical about its center. However, for an array limited to only four or five elements, the number of parameters that can be varied to optimize the design becomes very limited. A preliminary design has been done for a symmetric array of five elements with m' < 1. The elements were assumed identical so the only variable parameters are the magnitude of S_{21} and line lengths between elements. For simplicity, the feedline lengths were first taken to be equal (progressive phasing), and subsequently adjusted to give very near endfire condition at the lowest frequency (1.545 GHz). The array factor so obtained produces a high backlobe. It was determined, however, that by introducing a symmetric deviation from progressive phase this lobe can be greatly reduced.

(f) Non-Uniform Spacing

One way to add degrees of freedom to the design of symmetric arrays is to relax the requirement for constant spacing. This was considered worthy of consideration since the uniform spacing of ANSERLIN elements operating with m' < 1 is necessarily very close to one-half wavelength. As a result, an array with near-endfire phasing will have a space factor with a grating lobe intruding into the visible region. Some numerical experiments were performed with non-uniform spacing, but the most effective way to reduce the grating lobe appeared to be the reduction of inter-element spacing.

ARRAY CONSTRUCTION

(a) Microstrip Feed Lines

Although the original ANSERLIN elements were fed and terminated with small-diameter coaxial cable, this method is not conducive to a low-cost mass-produced fabrication process. Hence, all the array designs incorporate microstrip lines at the input and output, and in between the elements. The design of the transitions from microstrip to the annular sector is best accomplished with the aid of a time-domain reflectometer (TDR). After designing the components (microstrip, triangular fin, and annular strip) separately, to have the same characteristic impedance, they are joined to one another. The TDR display then indicates regions of the composite structure where significant deviations from the characteristic impedance occurs which can be fixed by slight alterations in the geometry in those regions.

(b) Double-Level Arrays

The microstrip feedlines must be placed very close to the ground plane to provide the proper impedance in a reasonable width and to prevent radiation. However, the annular sector of the ANSERLIN element has a higher separation from the ground plane to enhance the radiation. Originally, in ANSERLIN array designs, the microstrip lines and the annular sectors were placed on different levels. This technique is still preferred during initial stages of testing a newly designed array since it facilitates the alteration of spacing and feedline lengths. However, mass production of such arrays is not desirable.

(c) Single-Level Arrays

A new construction technique has been developed for this project which reduces the complexity and makes ANSERLIN arrays cost competitive with other approaches. The entire array, including the interconnecting microstrip phasing lines, is etched on one side of a thin dielectric substrate. Ground, plane for the phasing lines is provided on the back side of the substrate. However, the conductor is etched away underneath the radiating elements to provide larger spacing between them and a second ground plane. This variation in ground plane height inhibits radiation from the phasing lines and enhances radiation from the ANSERLIN elements. Metallic ramps are used under the input and output transitions between the phasing and radiating lines. The impedance at any point in the array, from feed end to termination, is maintained very close to the desired constant value. Hence, the input impedance is very nearly constant over a very wide band.

Figure 5 shows the artwork that was used to construct a four-element array. Note that m' > 1 type elements used in this array require large inter-element spacing approximately equal to 0.60 wavelength. Experience with previous arrays indicated that coupling between elements should not be a problem with this spacing. The difference in the geometry of the elements should also be noted. In this way, not only the main beam of the pattern is shaped but the grating lobe is also effectively controlled.

(d) Symmetric Arrays with Dual Polarizations Capability

Some drawbacks of the array of Figure 5 were addressed by studying symmetric arrays using ANSERLIN elements operating at m' < 1 mode. These elements are significantly smaller than those of Figure 5. However, the range of variation in the magnitude of S_{21} is also much smaller. This, together with the requirement for symmetry, leads to the conclusion that the practical elements of this variety will be almost identical. Hence, the starting point for designing arrays of this type is to take both the element geometry and the inter-element spacing as constant.

Figure 6 shows computed patterns for θ and ϕ polarization at mid-band for a symmetric five-element array using quasi-progressive, near-endfire phasing. The major problem with this design is the θ-polarized lobe near 20 degrees above the horizon ($\theta = 70°$) in the backlobe region. The problem is most severe at the lower band limit and essentially disappears at the upper band limit. A controlled deviation from progressive phasing (note the differences in the feedline lengths) has been used to reduce the response over most of the reverse coverage region, but the intrusion of the grating lobe into the visible region does not readily respond to this particular manipulation. However, it was considered unwise to be overly concerned about the theoretical behavior of the array at very low angles since the influence of the finite ground plane will alter significantly the array performance in that region.

TEST RESULTS

(a) Single-Level Array with Synthesized Pattern

Plots of realized gain versus elevation angle were obtained for the array of Figure 5 at JPL test facility. It was found that the antenna performed best over a band that was about three percent lower in frequency than desired. This is likely due to effects of the substrate material on the phase shift through the elements, an effect that was only estimated due to the lack of experimental data. Figure 7 shows the pattern measured at 1.55 GHz, the frequency corresponding to mid-band. The maximum gain is approximately 12.0 dB relative to a circularly polarized isotropic source, and the gain at 60 degrees above the horizon is about 9.0 dB, both well above the desired value of 6 db. However, the gain at 20 degrees above the horizon is close to 0 dB, and decreases further as frequency decreases. While this is lower than desired, the influence of the particular ground plane used in these measurements is certainly the greatest in this part of the pattern.

At JPL, the array was mounted on a 48 x 56 inch rectangular ground plane. Pattern measurements made at the University of Illinois with the same array mounted on a 36-in diameter circular ground plane agreed very well with the JPL data, except near the horizon. On the smaller ground plane the field at 20 degrees above the horizon was only 8 dB below the maximum, rather than almost 12 dB as shown in Figure 6. Other aspects of this pattern look particularly good. The level of cross polarization is quite low across the entire coverage region and the secondary lobes are down by 10 dB or more. As frequency increases, the coverage at 20° elevation improves, but the level of the lobes increases. The minor lobes are down by more than 15 dB at 1.475 GHz, but the gain at 20° above the horizon is -5 dB. A more realistic evaluation of performance at low angles can probably best be made by utilizing a ground surface that more closely approximates the size and shape of the vehicle in the vicinity of the mounting location. The measured return loss was approximately 10 dB over the entire band. The fact that this is significantly lower than the values observed for individual ANSERLIN elements is likely due to mutual coupling.

(b) Smaller Symmetric Array - Coupling Effects

Some preliminary measurements have been done on the array outlined in Figure 8. Note that the overall length of this five-element array is 16 inches as opposed to 19.5 inches for the four-element array of Figure 5. This reduction in size is made possible by using elements operating near m' = 0.8 so that they are much smaller in terms of the operating wavelength. To increase the radiation from these smaller elements, the height above the ground plane was increased beyond that used in the four-element array. The measurements on the array indicate detrimental effects possibly due to mutual coupling. The return loss is reduced and the pattern shape, particularly in the backlobe region, does not agree well with the computed array patterns which use the actual patterns of isolated elements but ignore coupling. The return loss was increased and better agreement with theoretical patterns were obtained after surrounding each element by a conducting fence. For a more practical solution, attention is being given to reducing the height, and perhaps adding very short fences (ridges in the ground plane).

CONCLUSIONS

Design, construction and test of a four element array of ANSERLIN elements demonstrated the successful application of synthesis methods that yield excitation coefficients for a difficult-to-realize radiation pattern. A single-level construction technique was developed that makes the production of array of ANSERLIN elements competitive in cost with arrays of other types of low-profile elements.

Work with a smaller five-element array has shown that reasonable pattern shaping can be achieved with a symmetric array that is capable of operating in either sense of circular polarization. Using smaller ANSERLIN elements produces potential problems with mutual coupling. Achieving good realization with present design procedures, that ignore mutual coupling, will depend upon developing practical ways to reduce the effects of the coupling. Some encouraging results in this direction have already been obtained.

Most of the requirements for MSAT applications, particularly those for low axial ratio and high return loss, have been met or exceeded by these arrays. The gain and coverage requirements have also been satisfied over a large portion of the frequency band. Several promising ideas, not yet been fully explored, indicate that ANSERLIN arrays can be successfully employed on mobile vehicles in the MSAT system.

ACKNOWLEDGMENT

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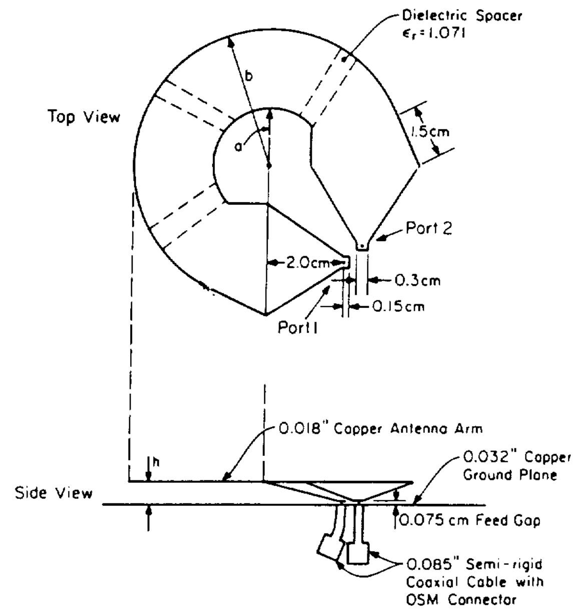

Figure 1. Geometry of an ANSERLIN element

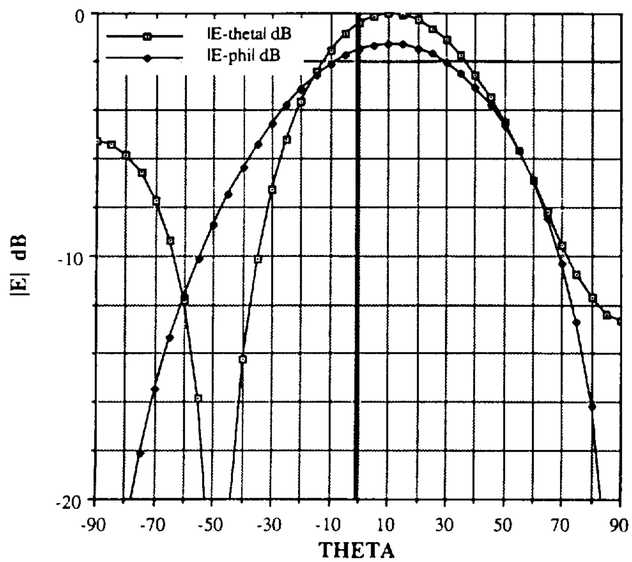

Figure 3. A typical element pattern in the plane of the array at 1.6 GHz (m' = 0.8).

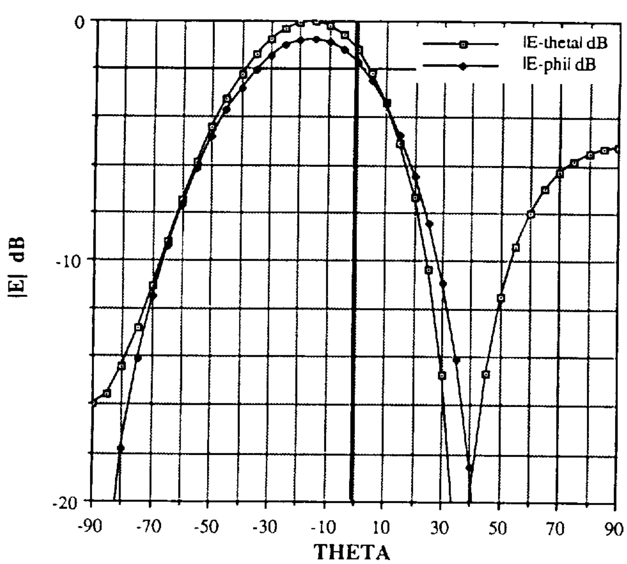

Figure 2. A typical element pattern in the plane of the array at 1.6 GHz (m' =1.25).

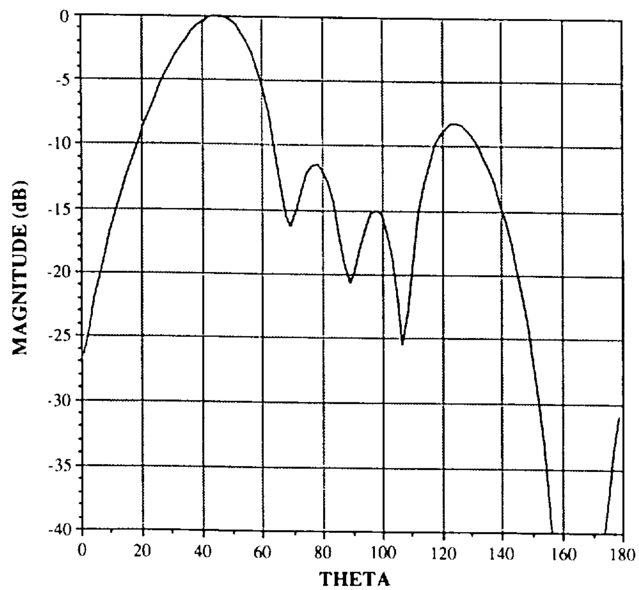

Figure 4. Predicted elevation patterns of 4-element array at 1.55 GHz.

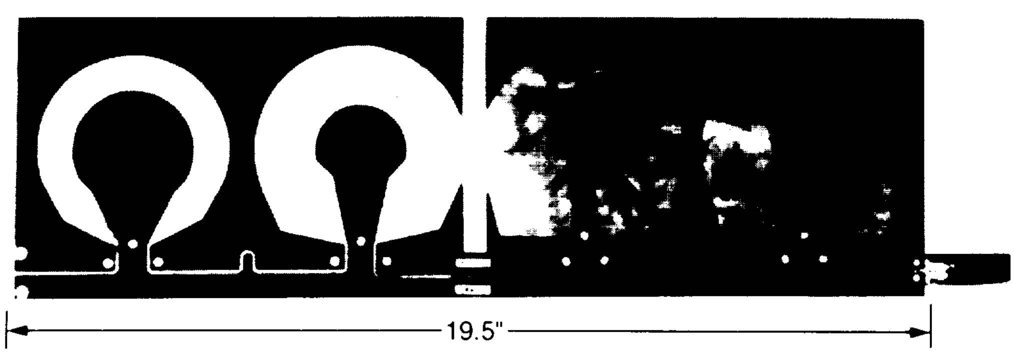

Figure 5. A pictorial view of the fabricated 4-element array.

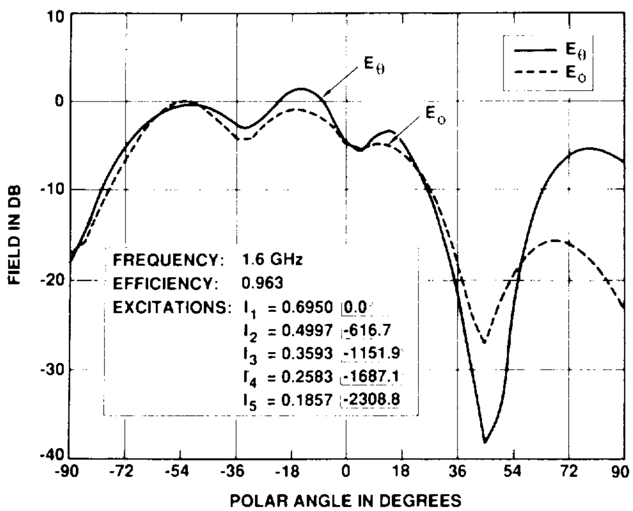

Figure 6. Computed elevation patterns of the 5-element ANSERLIN array at 1.6 GHz.

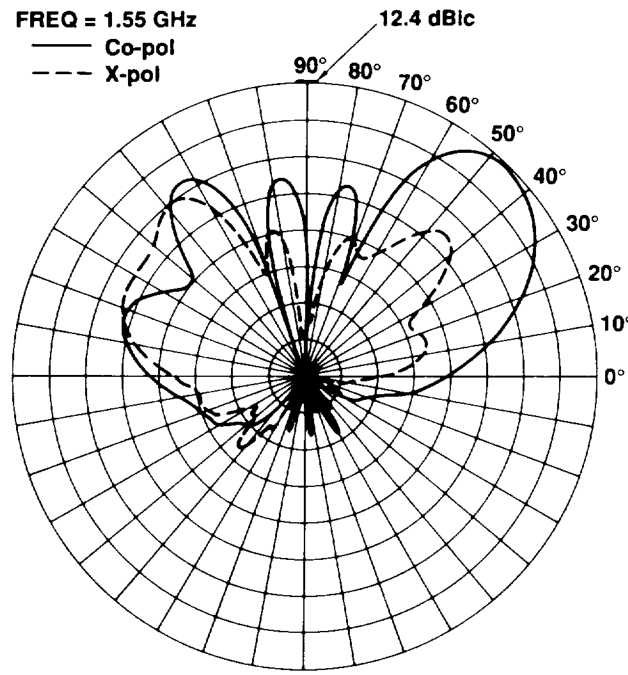

Figure 7. Measured elevation patterns of the 4-element ANSERLIN array at 1.55 GHz, on a 48" x 56" ground plane.

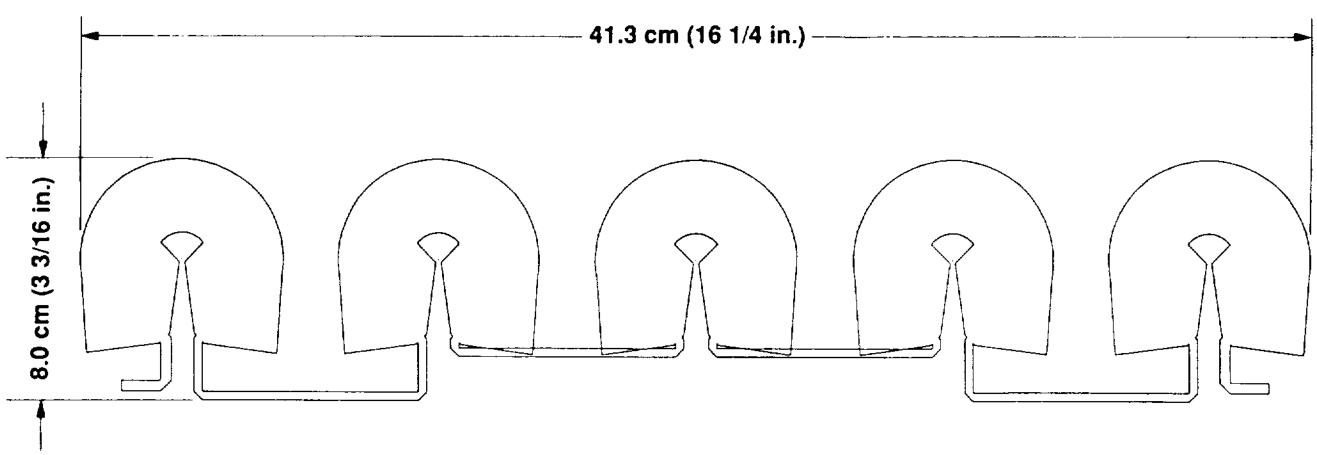

Figure 8. Outline of the symmetric 5-element array.